LISA telescope spacer investigations

J Sanjuán, A Preston, D Korytov, L Williams and G Mueller
University of Florida, Gainesville, FL, USA
J Livas, P Arsenovic, K Castellucci, J Generie, J Howard and R Stebbins
NASA/Goddard Space Flight Center, USA

Abstract

The large separation between the three SC in the LISA mission, 5 million kilometers, makes the telescope a key element of the Interferometric Measurement System (IMS). Each optical assembly in each SC includes a telescope pointing towards a far SC. The aim of the telescope is two fold: (i) it gathers the light coming from the far SC ($\sim$100 pW) and (ii) it expands and collimates the small outgoing beam ($\sim$1 W) and sends it to the far SC. Due to the very demanding noise requirements care must be taken in the design and validation of the telescope not to degrade the IMS performance. For instance, any fluctuation in the distance between the primary and secondary mirrors of the telescope will translate directly into phase noise in the IMS. This fact implies that the path-length noise in the telescope must be less than 1 pm $\mathrm{Hz}^{-1/2}$ in the LISA band. Also the telescope sets the shot noise of the IMS and depends critically on the diameter of the primary and the divergence angle of the outgoing beam. As the telescope is a rather fast telescope, the divergence angle is a critical function of the overall separation between the primary and secondary. Any long term changes of the distance of more than a a few micro-meter would be detrimental to the mission. Different configurations (on-axis/off-axis) and materials such as Silicon Carbide (SiC) and Carbon Fiber Reinforced Plastic (CFRP) are considered to be used in the telescope spacer structure. We will describe our experimental efforts to understand and quantify the behavior of different materials and also discuss a first investigation of a specific on-axis SiC telescope spacer for LISA. This work is supported by NASA contract 00069955.

Objective and requirements

Objective

- Develop and test a mechanical design for the main spacer element between primary and secondary
- Develop testing procedures for the telescope spacer
- Tolerance analysis identifies the M1-M2 (mirror 1-mirror 2) spacing as critical
- Mirrors and telescope are not part of the scope; just the spacer

Requirements

- The LISA telescope is for metrology not imaging: pathlength stability is key
- Two main requirements
  - Wavefront error is $< \lambda/30$ driven by the Strehl ratio (squared) requirement of 0.82 ($\lambda/20$)
  - Length stability

$$S_x^{1/2}(f) \leq 1\,\mathrm{pm\,Hz}^{-1/2}\sqrt{1+\left(\frac{1\,\mathrm{mHz}}{f}\right)^4} \qquad 30\,\mu\mathrm{Hz} < f < 0.1\,\mathrm{Hz}$$

  - Long-term stability: $\Delta x \lesssim 1\,\mu$m during mission lifetime
- On-axis design used initially because a tolerance analysis was available (off-axis design has similar requirements)
- Main emphasis in this work is on the demonstration of the length stability

On-axis tolerance analysis

- RMS WFE sensitivity

(units = nm WFE for μm or μrad motion). In parenthesis maximum allowed motions in μm or μrad for $\mathrm{WFE}_{\max}=\lambda/30$

pert.	x	y	z	rx	ry	rz
M1	1.7 (20.7)	1.7 (20.7)	21.6 (1.6)	0.9 (41.4)	0.9 (41.4)	0
M2	1.7 (20.7)	1.7 (20.7)	22 (1.6)	0.1 (365)	0.1 (365)	0
Lens	0	0	0.2 (152)	0	0	0
exit pupil	0	0	0	0	0	0

- Lens compensation
  - 87 μm motion of lens compensates 1 μm M2 axial motion
  - 0.2 nm RMS WFE results from 1 μm M2 axial motion with lens compensation
  - 5000 μm range of lens motion from nominal
  - 57.5 μm total range of M2 compensation (from nominal)

- Chief ray sensitivity

– OPL sensitivity (units=μm/μm or μm/μrad). In parenthesis maximum allowed motions in μm or μrad for $\mathrm{OPL}_{\max}=1\,\mu$m.

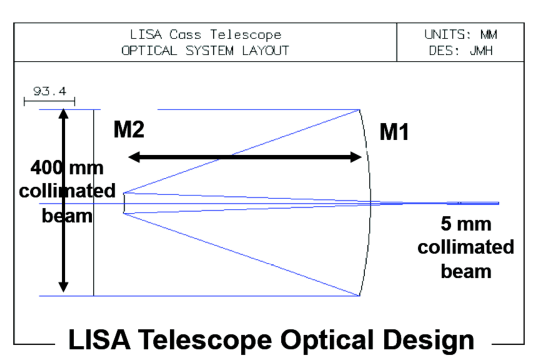
pert.	x	y	z	rx	ry	rz
M1	-2×10^{-6} (-0.5)	-2×10^{-6} (-0.5)	2 (5×10^{-7})	-10^{-6} (-1)	-10^{-6} (-1)	0
M2	8×10^{-7} (1.2)	8×10^{-7} (1.2)	-2 (-5×10^{-7})	-1.2×10^{-7} (-8.6)	-1.2×10^{-7} (-8.6)	0
Lens	8×10^{-7} (1.2)	8×10^{-7} (1.2)	0	6.8×10^{-10} (1466)	6.8×10^{-10} (1466)	0
exit pupil	0	0	1 (10^{-6})	0	0	0

– x-tilt sensitivity (units=μm/μm or μm/μrad). In parenthesis maximum allowed motion in μm or μrad for $x\text{-tilt}_{\max}=1\,\mu$rad

pert.	x	y	z	rx	ry	rz
M1	-149 (-0.007)	0	0	0	-151 (-0.007)	0
M2	133 (0.008)	0	0	0	17 (0.06)	0
Lens	16 (0.06)	0	0	0	-0.05 (-18)	0
exit pupil	0	0	0	0	1	0

– y-tilt sensitivity (units=μm/μm or μm/μrad). In parenthesis maximum allowed motion in μm or μrad for $y\text{-tilt}_{\max}=1\,\mu$rad

pert.	x	y	z	rx	ry	rz
M1	0	-149 (-0.007)	0	151 (0.007)	0	0
M2	0	133 (0.008)	0	-17 (-0.06)	0	0
Lens	0	16 (0.06)	0	0.05 (18.4)	0	0
exit pupil	0	0	0	-1 (-1)	0	0



LISA Telescope Optical Design

Materials and design

Material

- SiC selected as first candidate for the spacer material
  - Low coefficient of thermal expansion (CTE)
  - High thermal conductivity
  - Good strength/weight ratio
- Material properties are vendor and process dependent. Vendor chosen: Coorstek


SiC spacer parts (primary+struts)

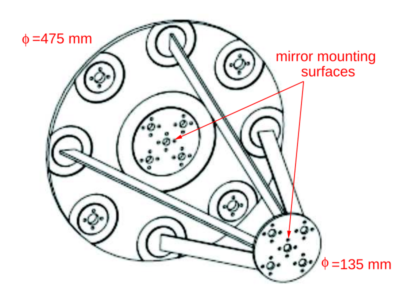
SiC (general) properties

Mechanical	value
density [g cm^{-3}]	3.1 (up to 4.1)
porosity [%]	0 (up tp few %)
flexural strength [MPa]	550
elastic modulus [GPa]	410
poisson ratio	0.14
compressive strength [MPa]	3900
hardness [kg mm^{-2}]	2800
fracture toughness K_{IC} [MPa m$^{1/2}$]	4.6
maximum use temperature [°C]	1650

Thermal	value
thermal conductivity [W m^{-1} K^{-1}] (at room temperature)	120 (100 to 200)
CTE [$\times10^{-6}$ K^{-1}] (at room temperature)	4
specific heat [J kg^{-1} K^{-1}]	750
Electrical	**value**
dielectric strength [ac-kv/mm]	semiconductor
volume resistivity [Ω·cm]	10^2 to 10^6 (dopant dependent)

Design

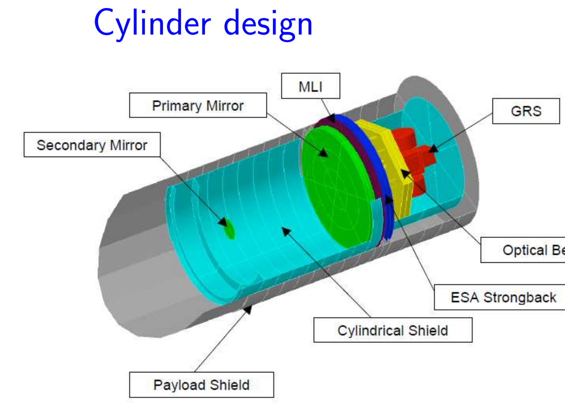
- Quadpod design chosen to prevent measurement errors in the quadrant photodetectors
- Diameter primary: 0.475 m (mirror 0.4 m)
- Diameter secondary: 0.135 m (mirror $\sim$0.05 m)
- Distance primary-secondary: 0.6 m



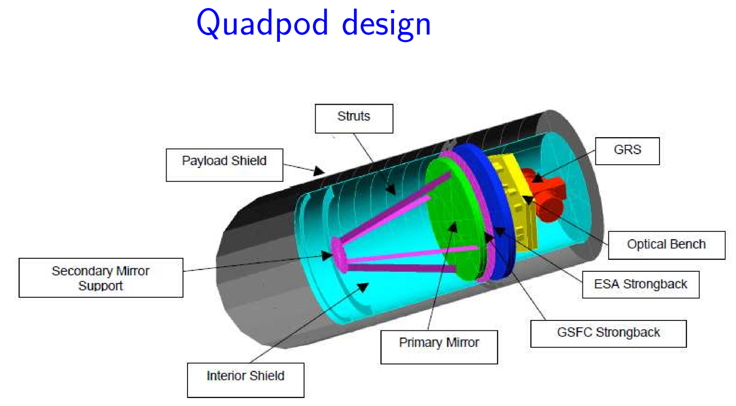
SiC spacer quadpod design

Thermal modelling: cylinder vs. quadpod

Cylinder design



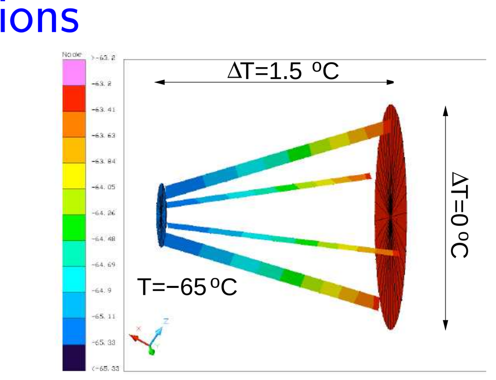
Quadpod design



Component	Cylindrical design temperature [°C]		Quadpod design Case 7 temperature [°C]		Difference [°C]
	Arm A	Arm B	Arm A	Arm B	
Inner (cylindrical) shield	-100.7 to -99.1	-101 to -99.3	-91.4 to -89.8	-87.2 to -86.1	+10
Primary mirror	-97 to -96.7	-97.2 to -96.9	-63.8 to -58.8	-69.0 to -63.5	+33
ESA strongback	-11.2 to -7.4	-11.4 to -7.9	-48.2 to -47.6	-51.9 to -47.2	-37
Optical bench	-6.1 to 7.5	-6.3 to 7.3	-28.0 to -12.4	-31.8 to -15.4	-22
Diodes	0 to 36.8	-0.4 to 35.4	-22.4 to 19.8	-25.5 to 17.4	-22

Thermal model to determine test conditions

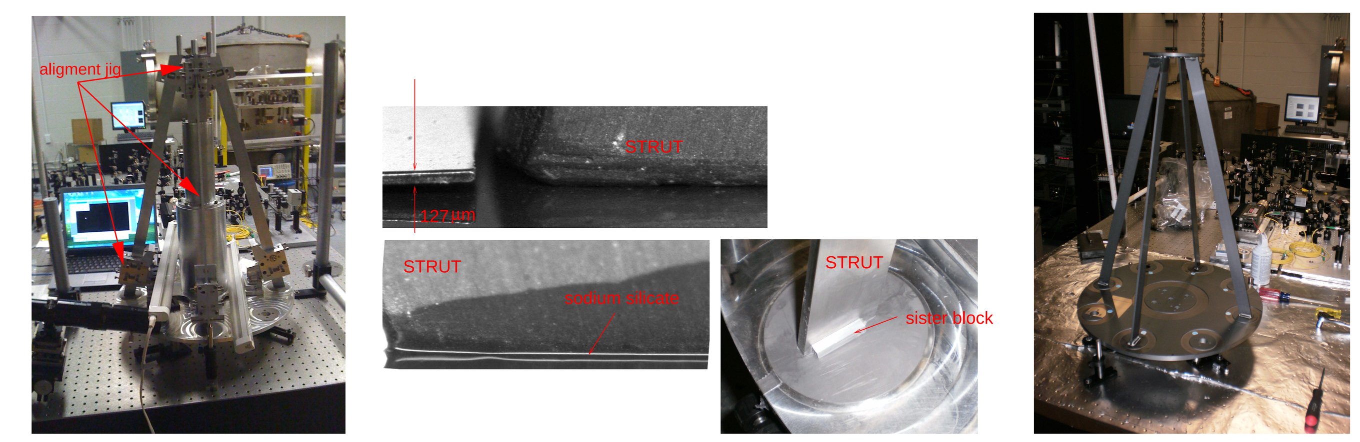
- Simplified model of Astrium's MTR layout
- Minor modifications
  - Removed MLI behind primary
  - Added second strongback (per IDL study recommendation)
  - Tweaked some emissivities
- Main interest is the spacer and understanding the heat flow (other mechanical elements/details may be not strictly correct but are included to set boundary conditions)



- Expected temperature -65 °C
- Difference between primary and secondary: 1.5 °C

Spacer assembly: alignment and bonding

- Alignment jig required to assemble the spacer
- Silicate bonding used in order to bond accurately the struts to the primary and secondary plates
  - Gaps come from: strut-end parallelism, different length struts, flatness of surfaces
  - Initially estimated gaps of $\sim$8 μm (nearly full strength)
  - Finally measured gaps of $\sim$30 μm
- *Sister blocks* glued by means of epoxy to the sides of the struts to provide strength to the joints



Left: alignment jig + spacer. Center: silicate bonding and *sister blocks*. Right: final quadpod assembly

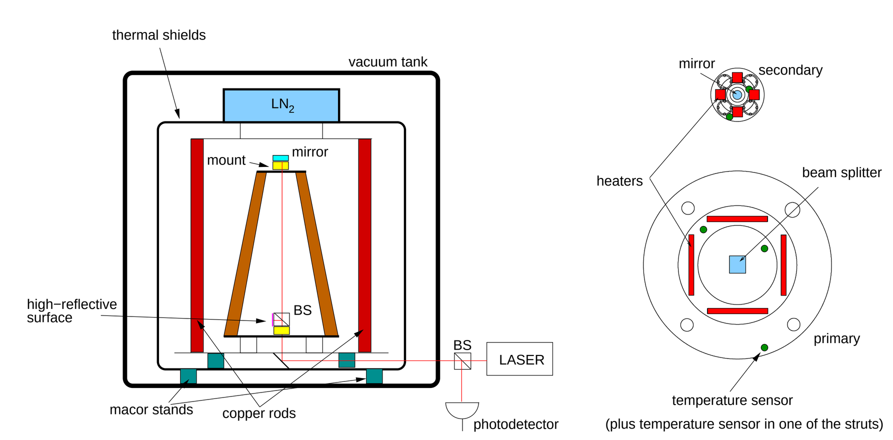
Test set-up, results & summary

The first set of experiments have been performed in order to:

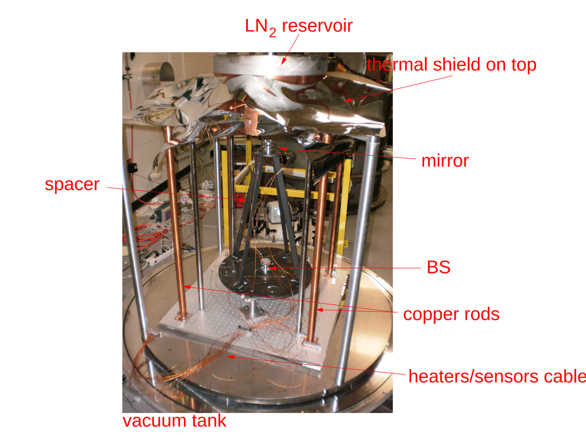
- Verify the ability of the spacer to handle the expected thermal conditions in LISA
- Assess the contraction of the spacer and compare it with Coorstek CTE values

We

- Cooled down the spacer to ~ -70°C: vacuum tank + liquid nitrogen
- Measured changes in length between primary and secondary: Michelson interferometer
- Measured and controlled the temperature of the spacer: Temperature sensors and heaters

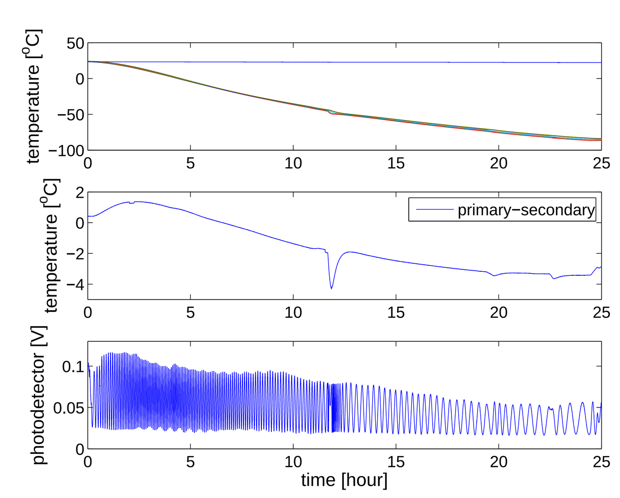


Vacuum tank filled with LN_2, Michelson interferometer and heaters and sensors



Spacer inside the vacuum tank (thermal shields not shown)

Results



- Spacer cooled down to -85 °C ($\Delta T = -97.5$ °C)
- Measured change in length: $-88.6\,\mu$m
- Expected change using Coorstek CTE: $-98.5\,\mu$m
- No significant tilts detected: *stationary* fringes over the measurement
- Spacer survived thermal cycling
- Measured CTE at -70 °C is 0.86×10^{-6} K^{-1} (Coorstek data-sheet 1.07×10^{-6} K^{-1}
- temperature fluctuations in the spacer must be $\leq 1.6\,\mu\mathrm{K\,Hz}^{-1/2}\sqrt{1+\left(\frac{1\,\mathrm{mHz}}{f}\right)^4}$ in the LISA band for CTE of 10^{-6} K^{-1}.

Summary

- Silicon Carbide is a viable candidate for a LISA telescope metering structure
- Verify the CTE values provided by Coorstek

ACKNOWLEDGMENTS: We wish to thank Pete Bender for illuminating discussions.

Future work

- Set up a Fabry-Perot cavity to perform stability measurements in the LISA band
- Long-term stability measurements
- Test other designs